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Method for Determining Permeability in Sandstone and Shale Reservoirs from Typical Drilling Parameters

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ABSTRACT: This paper describes a method for determining permeability variations for a continuous interval utilizing conventional drilling data for sandstone and shale reservoirs. The drilling data is used to find the unconfined compressive strength (UCS) within a well using an inverted rate of penetration (ROP) model. Previously published core and cuttings data for sandstone and shale reservoirs are used to create correlations for UCS and porosity as well as porosity and permeability. Porosity values can be calculated at any UCS values, and applied to the porosity and permeability correlation for the specific reservoir. This yields a permeability value for a specific reservoir at a given UCS. The verification of the correlation was done with permeability data from two wells penetrating the Montney shale and Nikanassin sandstone formations in British Columbia, Canada. The permeability calculation for the Montney and Nikanassin formations was compared to the permeability obtained from core and cuttings analysis data and a comparison between trend and accuracy can be done.

1. INTRODUCTION

Permeability determination can be a challenging task, but has proven advantageous to stimulation design and reservoir characterization. Determination of shale permeability has proven to be vastly different from the techniques employed for finding permeability in conventional reservoir rock (Moghadam and Chalaturnyk, 2015). The most common technique used to determine shale permeability is the GRI technique, but one of the downsides associated with this method is that the sample sizes used can alter the permeability results (Tinni et al., 2012). Civan et al., 2013, investigated the effect of Darcian flow on shale permeability and proposed that this method has the potential to predict shale permeability for a variety of conditions. One way that sandstone permeability can be determined is through the use of sonic and electrical logs, but these logs can be ineffective if shales are present (Jiang et al., 2013). Well logs can be used in conjunction with artificial neural networks or multiple regression analysis for permeability estimation (Pereira, 2004). There are also numerous correlations that utilize well logs to empirically determine permeability, including but not limited to the Timur, Tixier, and Coates-Dumanois, and Coates methods (Mohaghegh et al., 1997). Many of these empirically calculated permeability methods require knowledge of the irreducible water saturation, and often these correlations can be vastly different from core analysis results (Hunt and Pursell, 1997). One common issue with log methods is that depth correction between logs and core samples must be performed in order to obtain accurate results (Deng et al., 2013). Pressure transient data obtained from Wireline Formation Testers (WFT) can also be used for permeability determination, but it has been observed that this method may not be accurate in heterogeneous formations (Ramaswami et al., 2016). The cost of running WFT's can reduce the number of measurements taken in a well and can sometimes misrepresent the permeability for the entire zone in question (Li et al., 2016).

There have been a variety of techniques suggested for determining permeability in horizontal wells. Drill cuttings analysis is one way to determine permeability in a horizontal well, but it is necessary to analyze cuttings from various points along the lateral to obtain relatively accurate values (Haghshensas et al., 2016). Using a CT-scan technique to measure rock properties from drill cuttings has also been described, but the cuttings must be at least 2.5 mm or larger to be considered for testing (Siddiqui et al., 2005, Lenormand and Fonta, 2007). Using drill cuttings to determine permeability may be limited to samples whose porosity and permeability are within the ranges detectible by the equipment (Olusola, 2013). Another way for permeability determination, according to Kristiansen et al., 1996, involves using horizontal log data to estimate permeability when multiple-linear-regression, principal-component-regression, or partial-least-squares-regression is applied.

Another method that has been used to determine permeability involves correlating the permeability to porosity that has been determined from laboratory core testing. Skalinski and Sullivan, 2001 described a method to estimate permeability throughout a field but requires multiple cores from all differentiating facies within a wellbore as well as cores from various wells within the field; this is known as the Multivariate Facies Transform (MFT) method. Correlations between permeability and porosity is highly dependent on rock type as well as components like grain size, sorting, compaction, pore throat size, and cementation (Dahraj and Bhutto, 2014).

The above methods may provide relatively accurate permeability estimations, but they can prove costly and unreliable. Fleckenstein and Eustes, 2003, detail the issues that can arise from coring, including the cost for coring tools, rigtime costs, and core extraction locations. One limitation associated with logging techniques include issues in high-temperature wells (Briner et al., 2015). The use of measurement-while-drilling (MWD) or logging-while-drilling (LWD) and gamma ray (GR) tools are commonly run during the drilling process and are beneficial for formation evaluation in both vertical and horizontal wells (Gawankar et al., 2016).

2. APPROACH TO OBTAIN POROSITY FROM UCS

While there have been many correlations relating porosity to permeability, the techniques used to determine the parameters needed can be costly and often times, unreliable. In this paper, a technique that utilizes drilling data to determine unconfined compressive strength (UCS) and relates these values to porosity and permeability correlations is presented. The previously published porosity correlations (Cedola et al., 2017) can be correlated to permeability to obtain drilling data based porosity-permeability correlations that are specific to sandstone and shale lithologies. The correlations for determining porosity from UCS values, known as the Cedola sandstone and Cedola shale correlations, are presented in Eq.'s (1) and (2), respectively.

$$\emptyset_{Cedola\ Sandstone} = 424.8 * UCS^{-0.89} \quad (1)$$

$$\emptyset_{Cedola\ Shale} = 92.529 * UCS^{-0.63} \quad (2)$$

In Eq.'s (1) & (2), the UCS values were obtained from laboratory experiments. A UCS versus porosity plot for the Cedola sandstone and shale correlations is shown in Fig.'s 1 and 2 (Cedola et al. 2017).

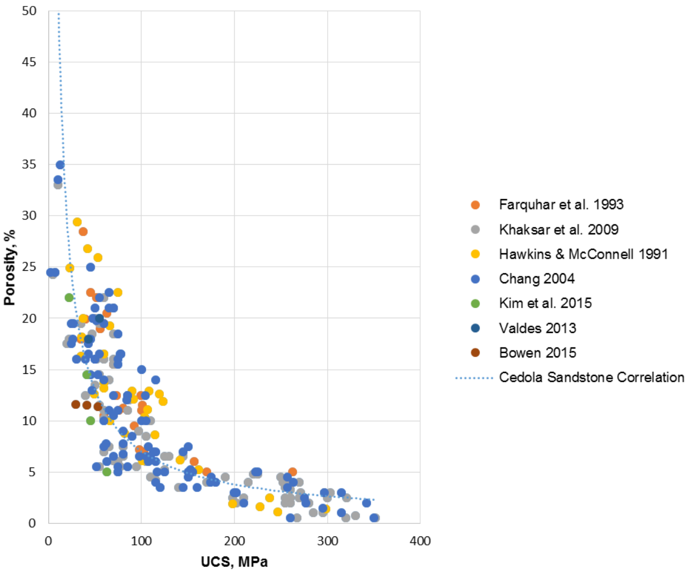

Fig. 1. Sandstone UCS and porosity data used to establish the Cedola sandstone correlation (Cedola et al. 2017).

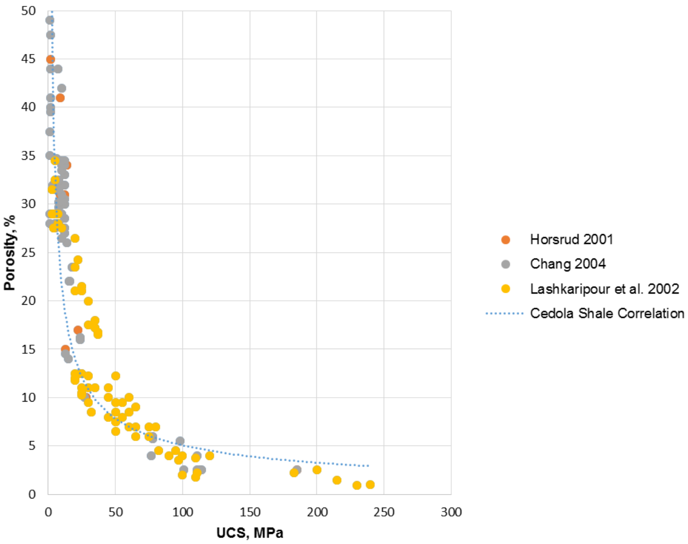

Fig. 2. Shale UCS and porosity data used to establish the Cedola shale correlation (Cedola et al. 2017).

UCS values can also be determined from drilling data by inserting the drilling data into inverted rate of penetration (ROP) models, which was originally developed for rollercone bits by Warren, 1987, and later revised by Hareland et al., 1993, and for PDC bits developed by Hareland et al., 1994, and later modified by Kerkar et al., 2014.

The UCS obtained from drilling data has been applied to the methods herein by Tahmeen et al., 2017, for different sandstone and shale reservoirs.

3. DEVELOPING SANDSTONE AND SHALE PERMEABILITY CORRELATIONS

Laboratory data can not only be used for correlating porosity and UCS, it can also be utilized in correlations between permeability and porosity. To develop such porosity-permeability correlations, porosity and permeability as found from core and cuttings analyses for various sandstone and shale formations has been collected and plotted (Figs. 3 and 4). Because of the variation in amounts of collected data for different formations, a 15% upper and lower margin on the best fit correlation has been plotted for each formation. Using the given data, porosity-permeability correlation for each specific sandstone and shale reservoir is found. It is seen that while the constants are different for each reservoir, the correlations for all sandstone and shale reservoirs take the same form shown in Eq. (3).

$$k = a * \emptyset^{b} \tag{3}$$

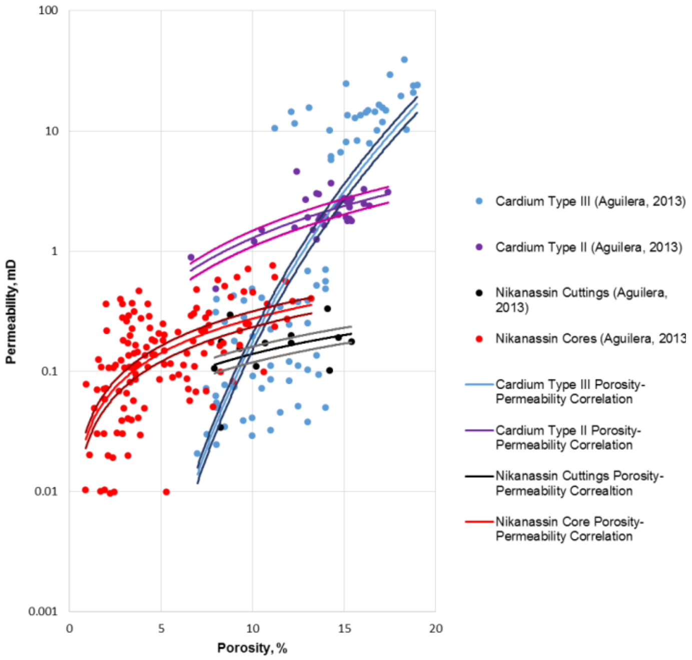

Fig. 3. Porosity versus permeability for collected sandstone data (Aguilera, 2013).

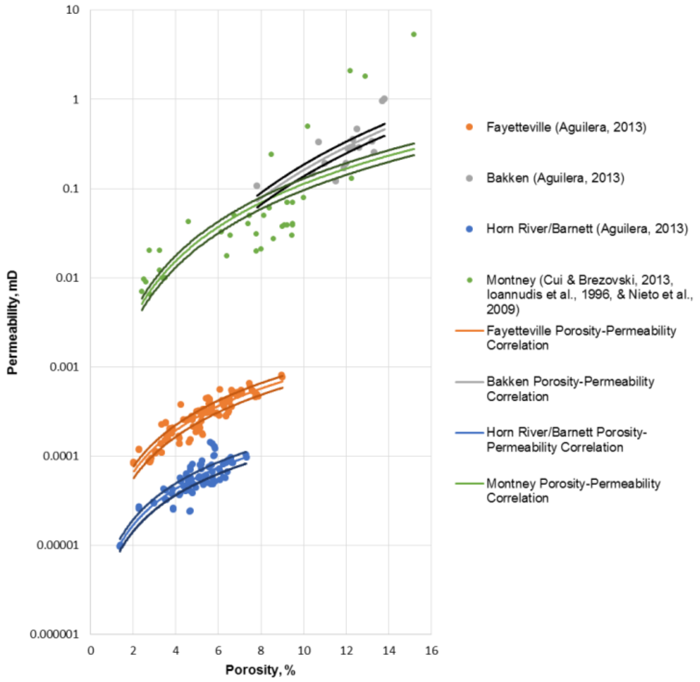

Fig. 4. Porosity versus permeability plot for collected shale data (Aguilera, 2013).

The collected porosity data can be inserted into the respective Cedola sandstone or Cedola shale correlation to obtain UCS values or the UCS can be inserted to determine the porosity. Because the porosity and permeability data has been collected and correlated, the UCS as determined from porosity can be plotted against the corresponding permeability data (Fig.'s 5 and 6).

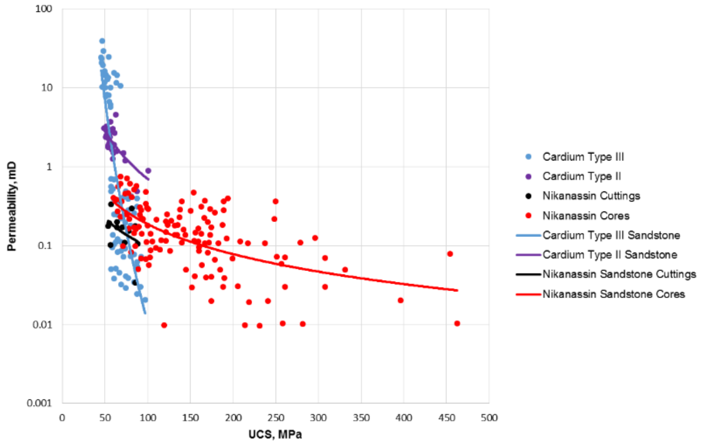

Fig. 5. Sandstone UCS versus permeability (Aguilera, 2013) plot.

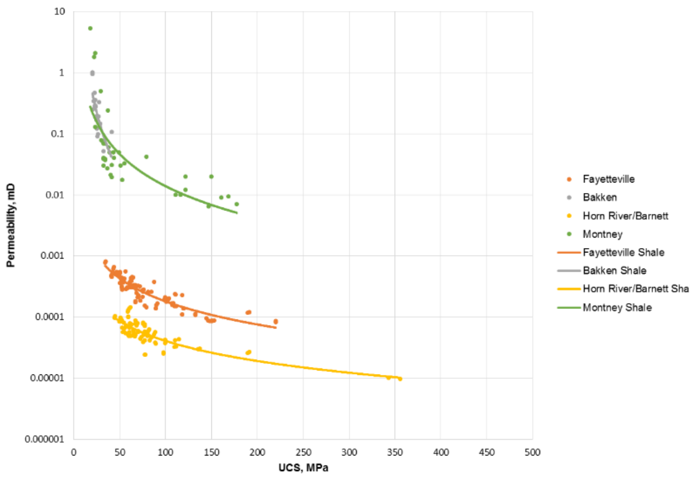

Fig. 6. Shale UCS versus permeability (Aguilera, 2013) plot.

4. DISCUSSION OF RESULTS

The porosity versus permeability plots shown in Fig.'s 3 and 4 for various sandstone and shale formations show that increasing the porosity will also increase permeability, however, some formations exhibit a much higher increase than others. For the sandstone plot, the Cardium Type III sandstones appear to have the largest range of permeability while the Nikanassin cuttings data doesn't experience much permeability increase over an approximate 7% porosity variance. The shale plot shown in Fig. 4 provides insight into how permeability can vary over different shale types and the 15% margins appear to include most of the published data.

The UCS-permeability plot for sandstone lithologies show that UCS decreases with increasing permeability (Fig. 5). In the Cardium Type III sandstone, the permeability decreases very rapidly over a short UCS range and the UCS-permeability correlation seems to fit the data fairly accurately. There is less collected data for the Cardium Type II sandstone and Nikanassin sandstone cuttings but the UCS-permeability correlation is still a valid UCS predictor given permeability. The collected Nikanassin core data was more spread out than the other data sets and appeared to have less of a trend than the other formations. In Fig. 6, the Fayetteville, Bakken, and Horn River/Barnett shales have similar trends and less variation than the collected Montney shale data. The Montney shale appears more scattered and has less of a trend between the UCS and permeability.

To observe how the porosity-permeability correlations compare to actual UCS-permeability data, UCS and permeability values for the Bakken shale, Montney shale, and Cardium sandstone were collected (Ghanizadeh et al., 2014). UCS values are input into the Cedola sandstone and shale correlations to determine porosity for the three reservoirs. The UCS-permeability correlations in Fig.'s 5 and 6 for the Bakken, Montney, and Cardium formations is plotted alongside the data points published by Ghanizadeh et al., 2014, (Fig. 7) and a comparison of the results can be made. The Bakken shale correlation appears to somewhat agree with the published data seeing as it matches one of the data points. For the other Bakken data, the correlation appears to be underpredicting permeability for two of the data points. The Montney shale correlation appears fairly accurate because it matches two of the three published data points. Because the published Cardium UCS versus permeability was limited and Nikanassin data was unavailable, the porosity-permeability correlations for these two sandstone formations were plotted to indicate the variation between the shale and sandstone trends.

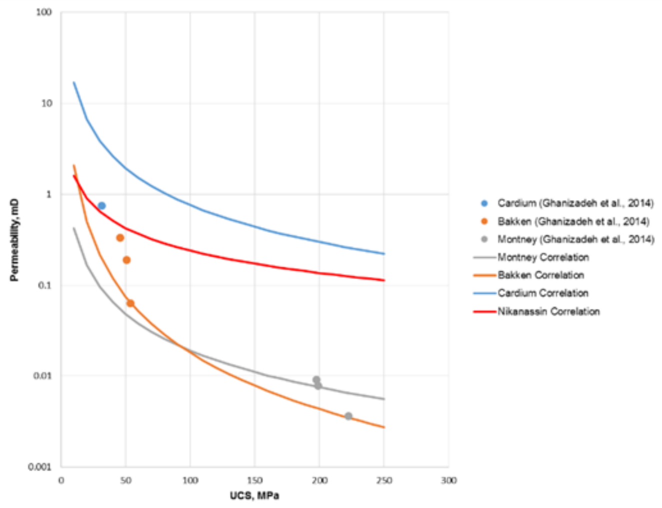

Fig. 7. Bakken, Montney, and Cardium UCS versus permeability data comparison (Ghanizadeh et al., 2014).

To observe the accuracy of the porosity-permeability correlations when applied to real-well applications, drill cuttings and core porosity and permeability data at specific depths from the Nikanassin sandstone and Montney shale formations in British Columbia, Canada has been collected. The collected porosity data was inserted into its reservoir specific porosity-permeability equation and permeability data can be found. The collected permeability and the permeability found from the porosity-permeability correlations can be plotted and compared (Fig.'s 8 and 9). The Cedola sandstone and shale porosity equations can be used to find and the UCS for each porosity measurement. In Fig. 8, the collected Nikanassin permeability was found from drill cuttings. For this reason, the Nikanassin cuttings porosity-permeability correlation was used to determine permeability. The correlated permeability appears similar in both trend and value to the collected permeability. The correlated permeability has less variance than the collected permeability and appears to be similar to the published Nikanassin permeability average, 0.05 mD (Gonzalez et al., 2012). The Nikanassin UCS is lower with high permeability values, which is the trend seen in Fig. 5. In Fig. 9 the collected Montney permeability was obtained from core analysis. The correlated permeability appears to have a similar trend to the measured permeability data. The correlated Montney permeability is similar in value to a majority of the published data, but may slightly under predict when measured permeability is considerably higher than typical shale values. According to Cipolla et al., 2011, the Montney shale has a permeability range of 0.001 mD to 0.05 mD. From the plot it can be seen that the correlated permeability is primarily within this range while the collected permeability data may be somewhat higher. The Montney UCS shows a similar but opposite trend to both the collected and correlated permeability, which is in agreement with Fig. 6.

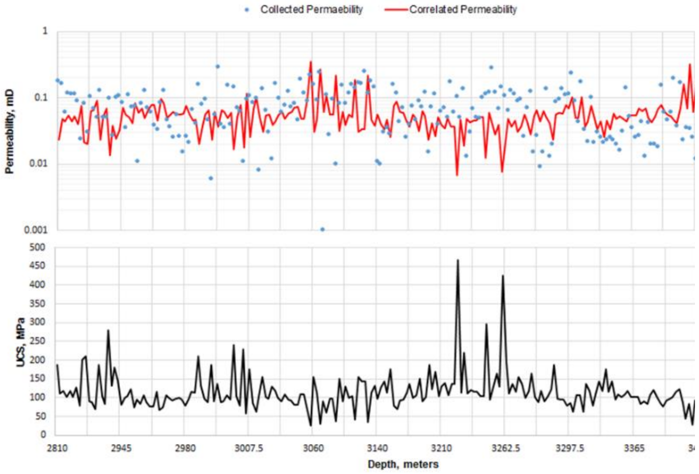

Fig. 8. Permeability comparison and UCS behavior for the Nikanassin sandstone (Flores, 2014).

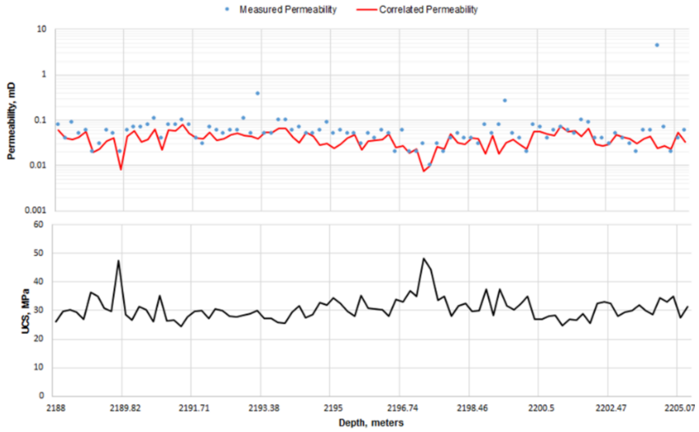

Fig. 9. Permeability comparison and UCS behavior for the Montney shale (Derder, 2012).

5. ADVANTAGES OF KNOWING PERMEABILITY

Permeability and other reservoir parameters are key components for stimulation design in horizontal wellbores. In horizontal tight shale gas wells, the use of wireline or LWD data has been used to estimate these parameters with the aim to identify “sweet spots”, or areas with higher porosity and permeability, to hydraulically fracture (Hashmy et al., 2011). Knowing permeability and porosity values in lateral sections can allow for better, more successful fracture staging and hydrocarbon recovery (Han et al., 2010). Having a better understanding of permeability and other reservoir characteristics can also minimize the number of stage needed when fracturing and reduce cost and time (Ashton et al., 2013). While log interpretation can provide permeability estimations, permeability determination in high-angle and horizontal wells can be an intensive task involving necessary physics-based simulation techniques (Polyakov et al., 2013).

Using drilling data to determine permeability and other reservoir parameters has many benefits, including that excess tools don’t need to be run because additional data doesn’t need to be obtained (Lehman et al., 2016). Permeability measurements can also have an impact on the overall performance of a well (Britt et al., 2004). Permeability determination from the use of drilling data can also have real-time application potential. Because drilling data is available for any point in a well, UCS, porosity, and permeability measurements can be determined in a short amount of time. Knowing these parameters can allow for the reservoir to be selectively stimulated. Real-time understanding of these variables can also allow for a reduction in stimulation costs, the ability to vary stimulation design based on parameter optimization, and determine the appropriate number of stages for successful hydrocarbon production (Acock et al., 1996).

6. CONCLUSIONS AND LEARNINGS

Using drilling data can predict UCS through inverted ROP models, and the correlations presented herein give the capability of predicting porosity and permeability from these UCS values. The UCS to permeability correlation presented in this paper is applicable to pure sandstone and shale formations but can be applied to any formation as long as a correlation between porosity and permeability is obtained. Many of the current methods used for permeability determination have a high price and/or extensive time to obtain results. Utilizing the correlation presented, permeability can be found in a much more economical and timely manner. Determining permeability from drilling data could allow for this method to be used in real-time applications. Optimizing the stimulation process is also highly possible when using permeability information. In horizontal wells, this information could optimize the completion design in that permeability values can be obtained at any point in the lateral. Knowing porosity and permeability throughout an entire well could impact hydrocarbon recovery, recompletions, formation evaluation, and numerous other aspects of drilling and completion operations.

NOMENCLATURE

UCS	Unconfined Compressive Strength, MPa
ROP	Rate of Penetration, meters per hour
WFT	Wireline Formation Testers
MFT	Multivariate Facies Transform
MWD	Measuring While Drilling
LWD	Logging While Drilling
GR	Gamma Ray
HLD	Mechanical Hardness
mD	milliDarcy
a,b	Formation Constant

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